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State of stress and age offsets at oceanic fracture zones and implications for the initiation of subduction

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ABSTRACT

The recycling of oceanic lithosphere back into the Earth's interior through subduction is a central component of plate tectonics. The process by which new subduction zones initiate, however, remains poorly understood. Several different mechanisms for subduction initiation have been proposed, including passive margin collapse (aided by sediment loading and/or rheological weakening due to the presence of volatiles) and forced convergence across a zone of preexisting lithospheric weakness. In this paper we focus on the latter type of model, which identifies three conditions necessary for subduction initiation: a zone of weakness such as a fracture zone, an age (and therefore density) offset along the fracture zone, and significant normal compressive stress which leads to shortening. We identify regions on the present-day Earth which meet these conditions and which may correspond to regions of relatively likely subduction initiation in the near future. Using a digital seafloor age model, we have created a database of oceanic fractures and quantified the associated age offsets. We have evaluated the state of stress on these lithospheric weak zones using two different global stress models. We find that the conditions needed to initiate subduction via the forced convergence model are relatively rare on the present-day Earth, and that there is little indication of incipient subduction at regions identified as relatively likely for subduction initiation. Using the same technique, we have evaluated the state of stress and seafloor age offset at regions of inferred present-day incipient subduction, and find that most of these regions are not associated with both high far-field compressive stresses and large age (and thus density) offsets. Subduction has likely initiated via forced convergence across preexisting zones of lithospheric weakness in the past, but our results indicate that the conditions needed for this type of subduction initiation are rare on the present-day Earth.

1. Introduction

Subduction, the sinking of oceanic plates into the mantle, is a central component of plate tectonic theory (e.g., Stern, 2002); it drives plate motion and allows for the formation of mid-ocean ridges. Once subduction begins, it is self-sustaining as the negative buoyancy of the older, colder, and denser subducting slab continues to pull the plate downward, thereby creating an asymmetric mantle downwelling (Gurnis et al., 2004). A self-sustaining subduction zone can also give rise to new subduction zones through transference or polarity reversal (Stern, 2004). The process through which new subduction zones spontaneously initiate, however, remains poorly understood. In order for oceanic lithosphere to begin to subduct, the considerable strength of the plate must be overcome by breaking and/or bending it (McKenzie, 1977), perhaps taking advantage of preexisting rheologically weak zones. The process through which this occurs remains uncertain, although many models have been suggested (e.g., Baes et al., 2011; Burov and Cloetingh, 2010; Cloetingh et al., 1984; Kemp and Stevenson, 1996; Mueller and Phillips, 1991; Regenauer-Lieb et al., 2001; Solomatov, 2004; Toth and Gurnis, 1998; Ueda et al., 2008). Yet, at some point, subduction zones must have initiated on an Earth without active plate tectonics (e.g., Hansen, 2007), and the initiation of new subduction zones has been a common occurrence throughout Earth's history; for example, ten new subduction zones of various lengths have initiated in the Pacific domain during the Cretaceous (Gurnis et al., 2004). To highlight one particular example, there is strong evidence indicating that the Izu–Bonin–Mariana system is a subduction zone that initiated (during the Eocene) independently of any existing subduction zone (Gurnis et al., 2004; Stern, 2004). The process through which subduction initiates, therefore, remains one of the important outstanding questions in plate tectonic theory.

Most studies of the subduction initiation process have focused on using either analog experiments (e.g., Goren et al., 2008; Leroy et

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al., 2004; Mart et al., 2005) or numerical modeling techniques (e.g., Gurnis et al., 2004; Hall et al., 2003; Nikolaeva et al., 2011; Toth and Gurnis, 1998) to model the formation of subduction zones, beginning with carefully defined initial and boundary conditions, to determine the combination of conditions that produces self-sustaining subduction. These studies generally seek to model physical processes that include the collapse of passive continental margins, perhaps with the aid of sediment loading or rheological weakening of the lithosphere, or the nucleation of a new subduction zone at a preexisting zone of lithospheric weakness. One example of the latter type of model includes the work of Gurnis et al. (2004), Hall et al. (2003), and Toth and Gurnis (1998), who invoke forced compression across a weak zone with a preexisting density difference, such as might be expected for an oceanic fracture zone. Gurnis et al. (2004) demonstrated that self-sustaining subduction could, indeed, be produced by such a mechanism, at least in the context of a two-dimensional numerical model. It remains unclear, however, how often the conditions needed to initiate subduction in this way (a preexisting zone of weakness, a density difference across that zone, and significant compression and shortening) actually occur on the Earth.

Here, we explicitly test the predictions of the Gurnis et al. (2004) model to determine where on the present-day Earth subduction might soon initiate (or might be currently initiating) by this process. We identified oceanic fracture zones as zones of preexisting weakness and calculate the difference between the lithospheric ages on either side of the fracture zone using a digital seafloor age model. We used two global stress models (Ghosh, 2008; Lithgow-Bertelloni and Guynn, 2004) in our calculations of the magnitude of normal compressive stress on each fracture. From these calculations, we identified locations with significant age offsets and relatively high compressive stress where subduction initiation may be relatively likely on the present-day Earth. We then examined global earthquake catalogs for evidence of anomalous seismicity in these regions that might be consistent with incipient subduction, as intraplate seismicity can indicate shortening and, perhaps, subduction initiation (e.g., Meuller and Phillips, 1991; Okal et al., 1986). Finally, we repeated our age offset and stress calculations for five regions which have been identified as likely sites of present-day incipient subduction (the Gorringe Bank, the Hjort Trench, the Mussau Trench, the Owen Ridge, and a proto-trench stretching from western Samoa to the Caroline trench) to evaluate whether subduction is likely initiating in these regions via the process modeled by Gurnis et al. (2004) or by some other mechanism.

2. Subduction initiation: models and observations

Since the development of plate tectonic theory, many different models for the initiation of subduction have been proposed and debated. Cloetingh et al. (1984) hypothesized that subduction initiates by passive margin collapse due to sediment loading, provided that the oceanic crust is young enough (since strength increases with age in oceanic lithosphere). The concept of passive margin collapse is consistent with the conceptual framework of the Wilson cycle of supercontinent assembly and dispersal and the opening and closing of ocean basins. Subsequent numerical modeling work demonstrated that additional external tectonic forces are needed to overcome the strength of the lithosphere and nucleate subduction, leading to the suggestion that existing weak zones located within plates are more potentially suitable for incipient subduction (Cloetingh et al., 1989). However, it has since been suggested that passive margin collapse may remain a viable mechanism for subduction initiation (e.g., Nikolaeva et al., 2010, 2011) if the lithosphere is significantly weakened, perhaps by hydration (e.g., Regenauer-Lieb et al., 2001). In particular, it has been suggested that the eastern US passive margin may be currently undergoing hydration due to the dewatering of the Farallon plate at depth (van der Lee et al., 2008) that may facilitate future subduction initiation.

The idea that subduction may initiate at preexisting weak zones has been studied by several different workers. Korenaga (2007) suggested that thermal cracking and subsequent serpentinization might produce localized weakening of the oceanic lithosphere and facilitate spontaneous subduction initiation. Modeling work by Hall et al. (2003) demonstrated that a fracture zone could progress into a self-sustaining subduction zone, provided that fault zone stresses are below ~20 MPa, that the net convergence rate is sufficiently fast to prevent excessive warming of the slab, that the fault zone is weak, that the coefficient of friction is low, and that the plate is young enough to allow for decoupling. Several studies have investigated how lateral density differences in the crust can facilitate subduction initiation (Goren et al., 2008; Lebrun et al., 2003; Mart et al., 2005; Stern, 2004). The lateral density difference can be at the boundary between continental and oceanic crust (Goren et al., 2008; Mart et al., 2005) or at a fracture zone or transform fault separating oceanic lithosphere of different ages (Lebrun et al., 2003; Stern, 2004) and may reflect compositional/petrological differences in the oceanic crust (Niu et al., 2003). Forced convergence across a weak zone may be provided by far-field tectonic stresses (e.g., Gurnis et al., 2004) or by mantle upwelling (e.g., Hynes, 2005; Ueda et al., 2008), and the subsequent transition from forced to self-sustaining subduction may be aided by non-Newtonian mantle rheology (Billen and Hirth, 2005).

In addition to modeling studies that attempt to re-create the subduction initiation process in a numerical or analog context, there have been many studies that have sought to characterize present-day incipient subduction through geological or geophysical indicators. For example, Meckel et al. (2003) used marine swath bathymetry/reflectivity, seismic reflection, gravity, magnetic, and teleseismic data to determine that self-sustaining subduction is not yet occurring at the Hjort Trench (Australian-Pacific plate boundary). However, anomalously deep earthquakes are present, indicating lithospheric deformation and underthrusting, which suggest subduction initiation (Meckel et al., 2003). Similarly, in studying the morphostructure of the Puysegur Ridge and Trench, Collot et al. (1995) found that incipient subduction is characterized by crustal shortening, ridge formation, and the development of an incipient trench. In a study of this same area, trench parallel normal faults and reactivated fracture zones were found to be characteristic of the region surrounding the incipient subduction zone (Lebrun et al., 2003), consistent with subduction initiation at a preexisting zone of lithospheric weakness.

In this study, we focus on the “forced convergence” mechanism for intraoceanic subduction initiation explored by Gurnis et al. (2004), Hall et al. (2003), and Toth and Gurnis (1998) through two-dimensional numerical modeling. This scenario invokes a preexisting zone of weakness in the oceanic lithosphere, a contrast across the weak zone in lithospheric age (and therefore density) that is needed to produce an asymmetric downwelling and to force the denser, more negatively buoyant plate into the mantle, and a significant amount of compression and shortening in the direction perpendicular to the strike of the weak zone. Oceanic fracture zones are thought to be a prime candidate for the nucleation of incipient subduction, because there are lateral density gradients associated with plate age offsets (Gurnis et al., 2004; Stern and Bloomer, 1992) and serpentinization may significantly weaken the oceanic lithosphere (e.g., Hilairet et al., 2007; Saleeby, 1984). Gurnis et al. (2004) performed a suite of numerical models exploring forced compression of oceanic fracture zones (in addition to former spreading centers and homogeneous plates) and found that significant shortening (~100–150 km) across a fracture zone can result in a transition from forced to self-sustaining subduction over a period of a few million years.

3. Data and methods

Digital isochron data from the EarthByte database (Müller et al., 1997) were used to identify locations of fracture zones with